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# TRACE Observations of Changes in Coronal Hole Boundaries

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**Abstract** Solar coronal holes (CHs) are large regions of the corona magnetically open to interplanetary space. The nearly rigid north–south CH boundaries (CHBs) of equatorward extensions of polar CHs are maintained while the underlying photospheric fields rotate differentially, so interchange magnetic reconnection is presumed to be occurring continually at the CHBs. The time and size scales of the required reconnection events at CHBs have not been established from previous observations with soft X-ray images. We use TRACE 195 Å observations on 9 December 2000 of a long-lived equatorial extension of the negative-polarity north polar CH to look for changes of $\gtrsim 5$ arcsec to $> 20$ arcsec at the western CHB. Brightenings and dimmings are observed on both short ($\approx 5$ minutes) and long ($\approx 7$ hours) time scales, but the CHB maintains its quasi-rigid location. The transient CHB changes do not appear associated with either magnetic field enhancements or the changes in those field enhancements observed in magnetograms from the Michelson Doppler Imager (MDI) on SOHO. In seven hours of TRACE observations we find no examples of the energetic jets similar to those observed to occur in magnetic reconnection in polar plumes. The lack of dramatic changes in the diffuse CHB implies that gradual magnetic reconnection occurs high in the corona with large ($\gtrsim 10°$) loops and/or weak coronal fields. We compare our results with recent observations of active regions at CHBs. We also discuss how the magnetic polarity symmetry surrounding quasi-rigid CHs implies an asymmetry in the interchange reconnection process and a possible asymmetry in the solar wind composition from the eastern and western CHB source regions.

**Keywords** Coronal holes · Magnetic fields

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## 1. Introduction

Solar coronal hole boundaries (CHBs) are long-lived ($\gtrsim$ days) separatrices between large-scale regions of predominately open CH magnetic fields and regions of generally closed magnetic fields. The closed fields form the bases of solar streamer structures, visible because of their higher densities of trapped plasmas. The CHBs play an important dynamic role in the formation of the solar wind. It is currently accepted that the fast ($\gtrsim 600$ km s$^{-1}$) solar wind arises from CHs and slow ($\approx 400$ km s$^{-1}$) solar wind from the more distributed open fields near CHBs or in active regions under the streamer structures (Esser, 1999; Wang and Sheeley, 2003; Schrijver and DeRosa, 2003; Liewer, Neugebauer, and Zurbuchen, 2004; Schwadron *et al.*, 2005a, 2005b).

At solar mid-latitudes CHs can be isolated unipolar regions or, during the declining phase of the solar cycle, equatorward extensions of the polar CHs (Wang, Hawley, and Sheeley, 1996; Insley, Moore, and Harrison, 1995). In the latter case the presence of north–south CHBs rotating quasi-rigidly despite the solar photospheric differential rotation was noted in Skylab X-ray images (Timothy, Krieger, and Vaiana, 1975) and in He I 10830 Å images (Insley, Moore, and Harrison, 1995). The rotation period is generally close to the $\approx$27-day solar equatorial period (Wang, Hawley, and Sheeley, 1996).

### 1.1. Concepts of Magnetic Reconnection at CHBs

CHBs are an essential feature of the model introduced by Fisk (1996) for solar transport of open magnetic field lines in the corona to explain the solar sources of the slow and fast wind. In the original version of the Fisk model (Fisk, Zurbuchen, and Schwadron 1999a, 1999b) the open field lines were transported by the convective and diffusive motions of the photospheric plasma along the solar surface in CHs and by magnetic interchange reconnection with large loops defining the magnetically closed regions of the streamer belt. The transport model was later generalized to include interchange reconnection in both the streamer belt and CHs (Fisk and Schwadron, 2001; Fisk, 2005). A recent version of the model (Fisk and Zurbuchen, 2005) discusses five transport mechanisms and the resulting distribution of coronal open fields. One of these mechanisms is convective flow due to differential rotation, which produces a retrograde (west–east) motion of open field lines at high latitudes in the frame rotating with the equatorial rotation rate.

Figure 1 shows schematically how interchange reconnection might operate to maintain the quasi-rigid CHBs against eastward photospheric convection. Loops convected into the CH at the western (W) CHB must be converted into open fields, and open fields convected out of the CH at the eastern (E) CHB must become closed. On the W CHB the reconnecting open and closed field lines have oppositely directed polarities, and the reconnection can occur near the loop footpoints (shaded region) to restore the CHB location and transport the open field eastward. At the E CHB the polarity of the convected open field lines matches that of the footpoints of the large-loop fields (shaded region) with which reconnection might occur. In that case reconnection more likely occurs near the end of the loop away from the E CHB or with a more favorably oriented smaller loop. The comparable schematic Figures 3 and 4 of Fisk, Zurbuchen, and Schwadron (1999a, 1999b) and Figure 1 of Schwadron *et al.* (2005a, 2005b) show only the E CHB shifts, but their figures are misleading in that they show the footpoint polarities of their long loops reversed from those of the E CHBs of our Figure 1. If reconnection at the E CHB occurs at the eastern end of the long loop, the CHB is properly shifted westward, but at the expense of a large eastward transport of the open field line. The Fisk model postulates comparable open loop footpoint displacements

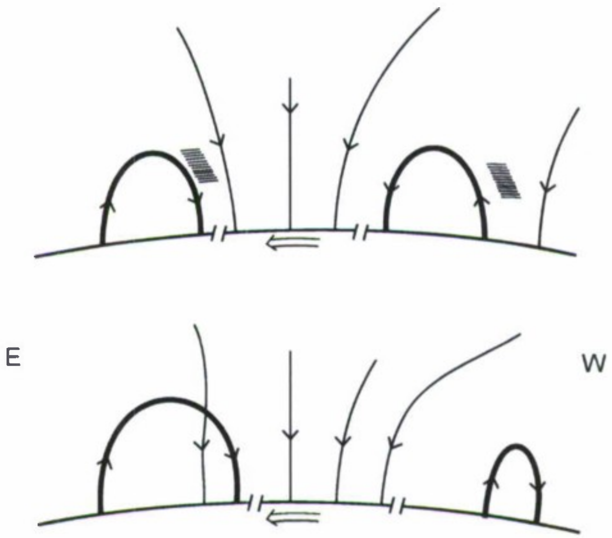


**Figure 1** Two-dimensional schematic showing the quasi-rigid CHBs shifting westward relative to the photospheric magnetic fields at high latitudes to compensate for the eastward shearing motion (bottom arrows) of the photosphere. In a fixed latitude profile of the CHBs interchange reconnection occurs in the shaded regions (top) between open (thin lines) and closed loop (thick lines) magnetic field lines. Arrows on lines indicate the magnetic field directions. The CHBs, shown as breaks in the photosphere, are shifted westward (bottom) after the interchange reconnections between the open and loop field lines. Reconnection with large loops at the W CHB (top right) is facilitated by the opposite field directions at the reconnection site (shaded) near the loop footpoint. Because the large-loop field direction at the E CHB is reversed from that at the W CHB, the reconnection region (upper left, shaded) is unfavorable for loop footpoint reconnection, so transport of the open field line (bottom left) must occur closer to the eastern end of the large loop or with a smaller loop near the E CHB (not shown).

in the large-loop regions on each side of the CH. Reconnection with small loops of random orientations at the E CHB could shift the E CHB but would violate the transport symmetry between the E and W CHBs, making the E CHB more diffuse than that of the W CHB. A similar schematic including a longitudinal perspective is shown in Figure 9 of Wang and Sheeley (2004), who distinguish between the different kinds of interchange reconnection at the E and W CHBs, also contrary to Figure 1 of Schwadron *et al.* (2005a, 2005b). Another schematic version of the E CHB (Figure 7 of Kahler and Hudson (2002, hereafter KH)) shows magnetic reconnection of two open field lines to form a disconnected U-shaped loop, which is presumed not to play a significant role at CHBs.

The quasi-rigid CHBs have been produced with sequences of current-free configurations derived from the potential-field source surface (PFSS) extrapolation (Wang, Hawley, and Sheeley, 1996), and are the basis for the CHB interchange reconnections described by Wang and Sheeley (2004). Although Fisk (2005) argues that potential-field models do not capture the processes that determine the coronal open fields, interchange reconnection also maintains the CHBs in the Fisk model (Fisk and Zurbuchen, 2005). Resistive MHD (Lionello *et al.*, 2005, 2006) models of coronal fields clearly show the expected conversion of closed to open magnetic flux at W CHBs and open to closed fluxes at E CHBs, as indicated in Figure 1.

### 1.2. Previous Observations of CHBs

CHBs are best observed in X-ray and EUV images, such as that of Figure 2, and should therefore be regions in which the magnetic reconnections between open and closed magnetic fields can be observed as the creation and destruction of bright loops. However, direct observations of these processes have been ambiguous. Using Skylab X-ray observations of an equatorial extension of a polar CH, Kahler and Moses (1990) found that CHB changes were effected by bright points (BPs). Their schematic explanation for CHB changes required the interaction of a small loop with a magnetic polarity reversed from that of the large-scale overlying loops at the CHB, a deficiency similar to that of Figure 1 of Schwadron *et al.* (2005a, 2005b) discussed above. KH studied changes in CHBs observed in *Yohkoh* Soft X-ray Telescope (SXT) images, but contrary to Kahler and Moses (1990), they found no role for BPs. However, in a recent study with 195 and 171 Å images by Madjarska and Wiegelmann (2009) the apparently random emergence and disappearance of BPs were the obvious primary CHB changes. They point out that the visibility of BPs is diminished in wavebands of progressively higher temperatures, which may explain why KH found no role for BPs in CHB changes. It is also not clear how open field lines can be globally transported across CHBs through the BP changes.

While BPs do form part of the CHBs at lower temperatures, the closed field regions at CHBs and the structures whose changes are important for forming the boundary layer between the slow and fast SW are the large-scale loops. The large $\gtrsim 10°$ lengths of the soft X-ray (KH) and 195 Å (Feldman, Widing, and Warren, 1999) loops forming CHBs support the suggestion of Wang and Sheeley (2004) and Wang, Biersteker, and Sheeley (2007) that interchange reconnection occurs primarily through those large loops. Wang and Sheeley (2004) interpreted their modeling result as evidence of continuous reconnection in the high corona involving small, stepwise displacements of field lines. They argued that interchange reconnection at the CHBs must occur between open field lines and large loops closing just below the PFSS. Wang, Biersteker, and Sheeley (2007) associate this interchange reconnection (their schematic Figure 9) with the formation of helmet streamers, structures separating CHs of opposite polarity. Ejecta along the newly opened CHB fields were associated with observed streamer blobs emitted at tips of helmet streamers very high ($r \approx 2.5\ R_{\odot}$) in the corona (Sheeley, 1997). The argument for high coronal interchange reconnection (Wang and Sheeley, 2004; Wang, Biersteker, and Sheeley, 2007) might be consistent with interchange reconnection at the E CHBs, but not necessarily with reconnection at the W CHBs, where reconnection with the opposite polarity footpoints of the large loops could occur at low altitudes (Section 1.1 and Figure 1). The large-loop role is also consistent with the requirement of the Fisk model (Fisk, 2005; Schwadron *et al.*, 2005a) that open field transport in closed-field regions occurs in large spatial steps by interchange reconnection with such loops.

The observational challenge is to detect those changes and understand the basic mechanisms involved. The KH study with the *Yohkoh* SXT images found those changes nearly always to be subtle and gradual at diffuse CHBs, where active regions are not present. Those CHBs were the most common of their three CHB types. In 195 Å images Bromage *et al.* (2000) found small-scale changes on time scales of a few hours in the CHBs of the Elephant's Trunk CH of 1996. Some CHB changes were closings and re-openings, and the main CHB persisted for several months. Similarly, besides the BP changes, Madjarska and Wiegelmann (2009) found some CHB displacements not related to any structure distinguishable in 195 or 171 Å images. Bidirectional jets were observed in a CH in transition region lines by Madjarska, Doyle, and van Driel-Gesztelyi (2004). Although they were taken as a

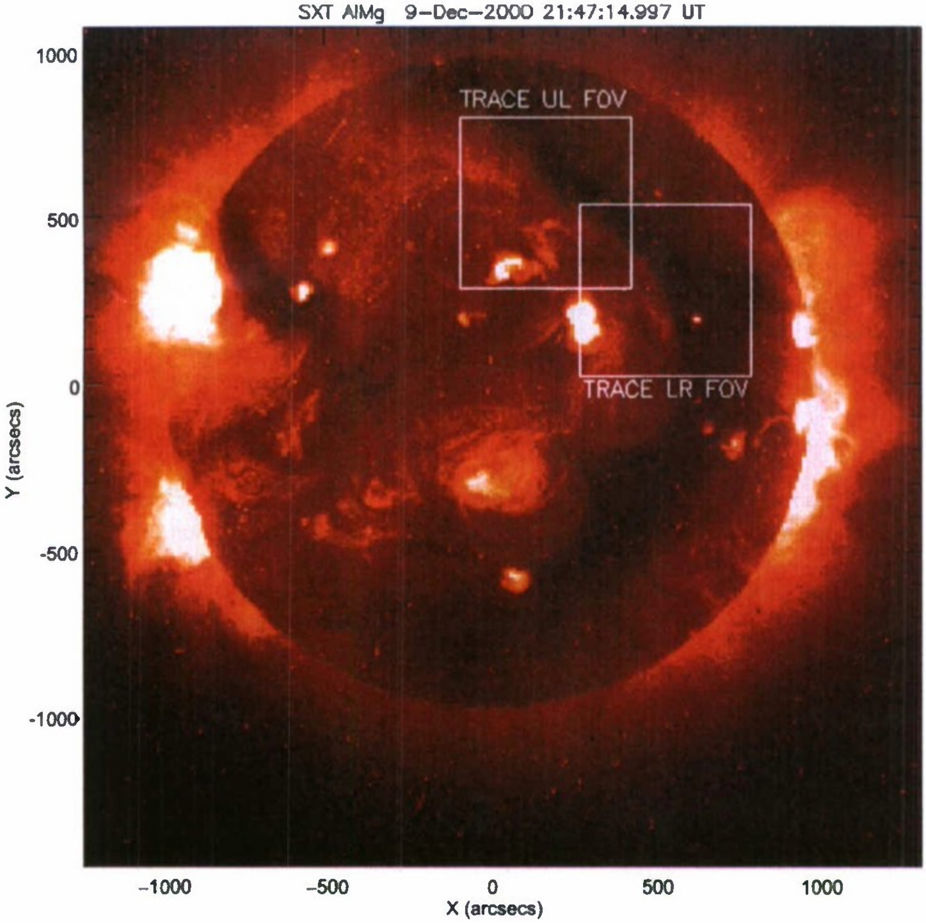


**Figure 2** The *Yohkoh* SXT soft X-ray image of 9 December 2000. A long equatorial extension of the negative-polarity north polar CH is apparent as the dark band in the western hemisphere. The TRACE upper left (UL) and lower right (LR) FOVs are indicated with superposed boxes. Our analysis was limited to the western CHB to avoid projection effects. Active Region 9254 lies on the edge of the LR FOV.

signature of reconnection at CHBs, it appeared that the jets were characteristic of the CH area rather than of the CHB, as pointed out by Wang and Sheeley (2004). Macrospicules observed inside CHs with off-band H$\alpha$ and C IV 1550 Å images (Yamauchi, Wang, and Moore, 2005) have been taken as evidence of interchange reconnection, but these phenomena also appear to arise within the CH rather than at CHBs. An observed correlation of transition-region and chromospheric EUV emission-line intensities across the CHB regions of a quasi-rigidly rotating CH was interpreted by Raju *et al.* (2005) to indicate that magnetic flux transport across the CHB was not impeded. The observed decreased correlation of coronal-line intensities across CHBs implied a continuous magnetic reconnection in the corona.

While there is obviously general agreement that the open and closed magnetic fields must be transported across CHBs by supergranular diffusion and differential rotation, we do not have coronal observations adequate to characterize the required magnetic reconnection process. In particular, we would like to know the time and size scales of the interchange

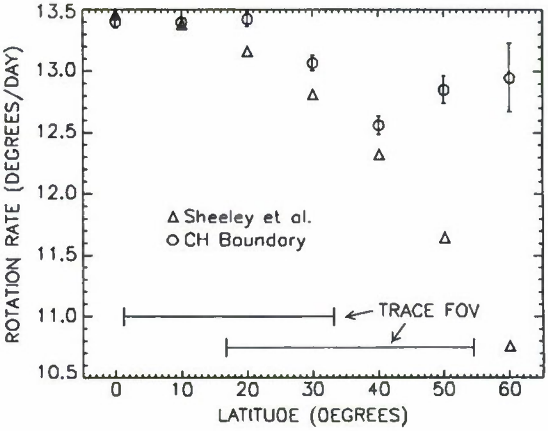


**Figure 3** The rotation rates of the W CHB from central meridian passages observed on He 10830 Å maps. Triangles indicate the slower rotation rates of magnetic features determined by Sheeley, Wang, and Nash (1992). The quasi-rigid rates of the CHB contrast with the differential rotation of the magnetic features. The latitudinal extents of the TRACE LR and UL FOVs of Figure 2 are shown at the bottom.

reconnections. If we accept the concept illustrated in Figure 1, then the most energetic reconnections might involve the largest loops outside CHs. The conversion of one end of a bright large loop into a dark open field line or vice versa should be most obvious as a shift of a CHB. The SXT soft X-ray observations by KH, who generally failed to find discrete shifts at CHBs, were limited by $\approx 5 \times 5$ arcsec pixels and $\approx 1$ hour time resolution. Here we take advantage of the superior spatial and temporal resolution of the Transition Region and Coronal Explorer (TRACE) satellite to look for changes in CHBs of a quasi-rigidly rotating CH.

## 2. Observations of CHBs

### 2.1. Observational Requirements and Selection

As in the earlier work of KH with SXT images, the goal is to observe CHB changes at a long-lived extension of a polar CH with high time and spatial resolution. Observations with the TRACE instrument (Handy *et al.*, 1999) provide $0.5 \times 0.5$ arcsec pixel resolution over an 8.5 arc minute field of view and time resolution as short as about 4.4 minutes. TRACE and SOHO/EIT observations with the 195 Å line of Fe XII, which provides a temperature response range of $1-2 \times 10^6$ K, generally show well defined CHBs. We therefore sought periods of extensive ($\gtrsim 5$ hrs) TRACE 195 Å observations of a long-lived polar CH extension, near central meridian passage and over a large range of solar latitudes. Of the TRACE CH observations we selected those of 9 December 2000 as the optimum set. Figure 2 shows the two TRACE fields of view (FOV) (UL is for upper left, centered at $x, y = 100, 558$ arcsec; LR is for lower right, centered at $x, y = 455, 270$ arcsec) superposed on the daily SXT image. Observations of those regions in the 195 Å line were carried out from 0824 to 1548 UT with a 4.4 min time resolution over most of that period. An important part of our analysis is to compare photospheric magnetic field enhancements and changes with the CHB features and changes. Photospheric magnetic fields of the TRACE FOV were mapped by the SOHO Michelson Doppler Imager (MDI, Scherrer *et al.*, 1995) in a special 4 minute rate during 09:40–22:00 UT, in addition to the normal full-disk images with a 96 minute cadence. The MDI field detection threshold is $\approx 50$ G (gauss), but with an appropriate algorithm can be reduced to 17 G (Schrijver *et al.*, 1997).

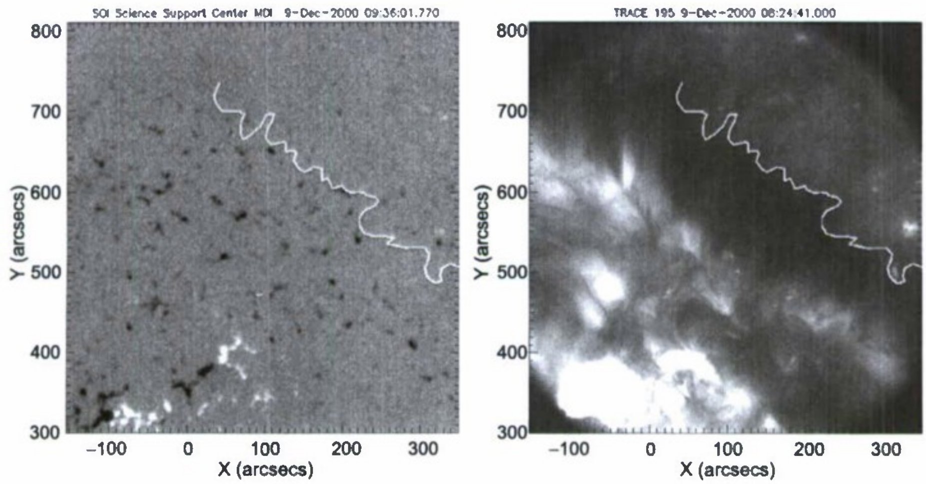


**Figure 4** The UL CHB outline projected on the 9 December TRACE 195 Å image at 08:24 UT (right) and on the aligned MDI magnetogram at 09:36 UT (left). The UL FOV is shown in Figure 2.

The selected CH was YCH3, one of three long-lived *Yohkoh* SXT CHs analyzed by KH. One of their YCH3 analysis periods was 6–8 December 2000, when YCH3 was near central meridian. YCH3 was an equatorial extension of the negative-polarity north polar CH observed over Carrington rotations 1968 to 1971. We used the KPNO He 10830 Å CH maps to measure the locations of the W CHB at central meridian passages as a function of latitude over the five Carrington rotations 1967 through 1971 (16 September through 3 January). Figure 3 shows that the CHB rotation rates at all latitudes were faster than those given for photospheric magnetic fields by Sheeley, Wang, and Nash (1992). In most of the TRACE FOV that difference is $\approx 0.3^\circ$ per day. This confirms that the magnetic fields at the W CHB must be converting from predominately closed to open fields to offset the gradual effect of the photospheric differential rotation to convect closed fields eastward into the CH.

## 2.2. Data Analysis

We restrict our observations to only the limbward (W) CHB to avoid projection effects expected from the super-radial divergence of open coronal fields at the CHBs (KH). On each TRACE 195 Å UL and LR image we visually traced out the W CHB. Scattered light affects the brightness of both CHs and loops at the CHBs (DeForest, Martens, and Wills-Davey, 2009), but it should have no measurable affect on the CHB locations, where the brightness gradients are high. With the image brightness level we used, the CHB contours were repeatable on each image to $< 3$ arcsec. Figures 4 and 5 show the CHBs outlined on typical aligned MDI photospheric and TRACE 195 Å images of the UL and LR FOVs. The CHB contours allowed us to compare any pair of different 195 Å images to determine the CHB changes over the time interval between those images.

Viewing of the CHB movies over the full observing period shows gradual variations of the CHBs with no indications of bright jets or flare-like events that might signal coronal magnetic reconnection. From visual scans of the movies we find that over the $\approx 7$ hour observing period the CHB location was continually fluctuating by means of the changes of up to $> 20$ arcsec, but it was also continually restored to the same well defined location. This is obvious from Figure 6, which shows 195 Å LR images with pairs of CHBs at different

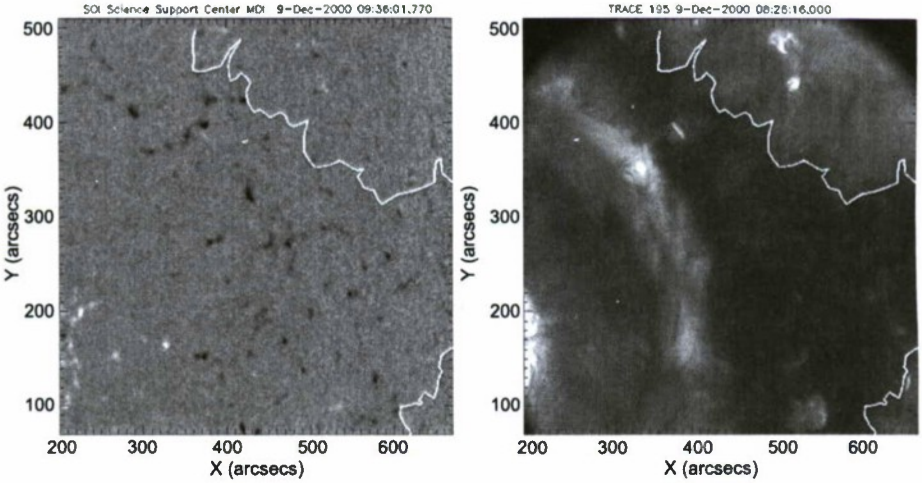


**Figure 5** The LR CHB outline projected on the 9 December TRACE 195 Å image at 08:26 UT (right) and on the aligned MDI magnetogram at 09:36 UT (left). The LR FOV is shown in Figure 2.

times marked with white and gray lines. The three panels show CHB changes over times of 4.4 minutes, 1 hour and 7 hours. In each case we find significant changes of $\lesssim 20$ arcsec, exceeding the $< 3$ arcsec uncertainty of each CHB. However, the displacements of the two CHBs from each other are similar on all three time scales and are essentially time independent.

To assess the importance of magnetic field structures for CHB changes, we qualitatively compared the locations of the largest observed CHB changes with the photospheric field features. We found no obvious association of the large CHB changes with regions of enhanced magnetic field intensities. In the inverse study we selected the largest temporal changes in the magnetograms from differenced MDI images to compare with the CHBs and CHB changes, but again we found that the largest magnetic field changes bore no obvious association with either the CHB structures or their changes.

## 3. Discussion

### 3.1. Reconnection at CHBs

The earlier KH study of CHBs of three quasi-rigidly rotating CHs with the *Yohkoh* SXT images covered a combined observing period of about 27 days with $\approx 1$ hour time resolution and half-resolution pixel sizes of $4.9 \times 4.9$ arcsec. Our study is complementary to theirs in that with TRACE observations we have much higher temporal ($\approx 5$ minutes) and spatial (1 arcsec pixels) resolution and simultaneous magnetograms from MDI. Our study covers 7 hours and, to avoid projection effects, we examined only the western CHB. The $1.0-2.0 \times 10^6$ K temperature response of the TRACE 195 Å passband (Handy *et al.*, 1999) is lower than the $2.5-10 \times 10^6$ K response of the SXT (Tsuneta *et al.*, 1991), but the CHBs and adjacent closed field structures consisting of hot ($\approx 1.4 \times 10^6$ K) loops exceeding 1 arcmin (Feldman, Widing, and Warren, 1999) are similar in the two instruments.

In both the KH and our study the dominant observed bright coronal structures at CHBs were long ($\gtrsim 10°$) loops. The CHB changes occurred as these loop footpoints brightened or darkened. We looked for any explosive events or eruptions that might have signaled episodes of the presumed interchange reconnections, but, like KH, found none. Neither bright points nor large-scale eruptive transients played roles in the changes to CHBs that we observed. In the much longer observing period of their study KH found six large-scale transients on CHBs, but none of those was associated with a long-term change in the CHBs. Thus, combining the two studies, CHB changes were observed, but not in the form of explosive transient brightenings such as subflares or jets. This result is consistent with the 195 Å small-scale changes observed at the CHB of the quasi-rigidly rotating Elephant's Trunk by Bromage *et al.* (2000), but while the time scale of their CHB changes was a few hours, we find changes over the length of the CHB on time scales ranging from several minutes to many hours. These changes of loop brightness occur in the context of long-lived (days) quasi-rigidly rotating CHBs.

The MDI images of Figure 4 clearly show a dominant negative magnetic polarity within the CH and a mixed polarity in the closed field regions to the west of the CHB, but we found in general that 195 Å loop brightenings and dimmings were not associated with obvious magnetic features or with any observed changes in the magnetic structures. The magnetic sensitivity of the MDI is limited to $\approx 50$ G (Scherrer *et al.*, 1995), so we would not have been able to observe any changes in weaker fields accompanying the loop changes.

The results of this study support the view (Wang and Sheeley, 2004; Wang, Biersteker, and Sheeley, 2007) that gradual interchange reconnection occurs at high altitudes, perhaps as high as the assumed PFSS at $\approx 2.5 R_{\odot}$. The reconnection is continually occurring to maintain a stable long-lived CHB on all time scales exceeding our $\approx 5$ minute time resolution as we showed in Figure 6. The large-scale quiet corona appears to be dominated by a plasma $\beta$ of unity and by long ($L > 10^5$ km) hot ($T_e \approx 1.4 \times 10^6$ K) loops (Feldman, Widing, and Warren, 1999; Feldman and Widing, 2003) with relatively low ($\approx 1/L$) coronal heating rates (Schrijver and van Ballegooijen, 2005). The heat capacity of the large loops newly formed in the interchange reconnections may be sufficiently large that the released reconnection energies are adequate to heat them only over time scales of minutes or longer to X-ray brightness. Similarly, the X-ray emitting plasma from loops converted to open fields will escape on those time scales to effect a gradual decrease in the observed X-ray brightness. The outflowing plasma probably constitutes the slowly ($\lesssim 250$ km s$^{-1}$) moving streamer blobs observed in the SOHO coronagraph (Wang *et al.*, 1998).

The observational signatures of the CHB loop dynamics in this study are limited to a single emission wavelength. The presumed processes of CHB loop openings and closings with their changes in temperature structures and material outflow rates can be observed to great advantage with the instrument suite on the *Hinode* spacecraft. Any magnetic field variations down to several G can be observed at the loop footpoints with the Solar Optical Telescope (SOT), which also provides observations of line emission originating from the low photosphere through the chromosphere (Tsuneta *et al.*, 2008). The EUV Imaging Spectrograph (EIS) can detect changes in outflow velocities expected from the changing loop magnetic topologies (Culhane *et al.*, 2007), and the X-ray Telescope (XRT, Golub *et al.*, 2007) can observe the changes in loop brightness and temperature at CHB reconnection sites. Related *Hinode* studies of flux emergence and flux cancellation at a CHB (Yang *et al.*, 2009) and of outflows from an active region edge at a CHB (Sakao *et al.*, 2007) did not use the full *Hinode* instrument suite, which could advance our understanding of the sources of the slow solar wind and of open field transport through CHB studies.

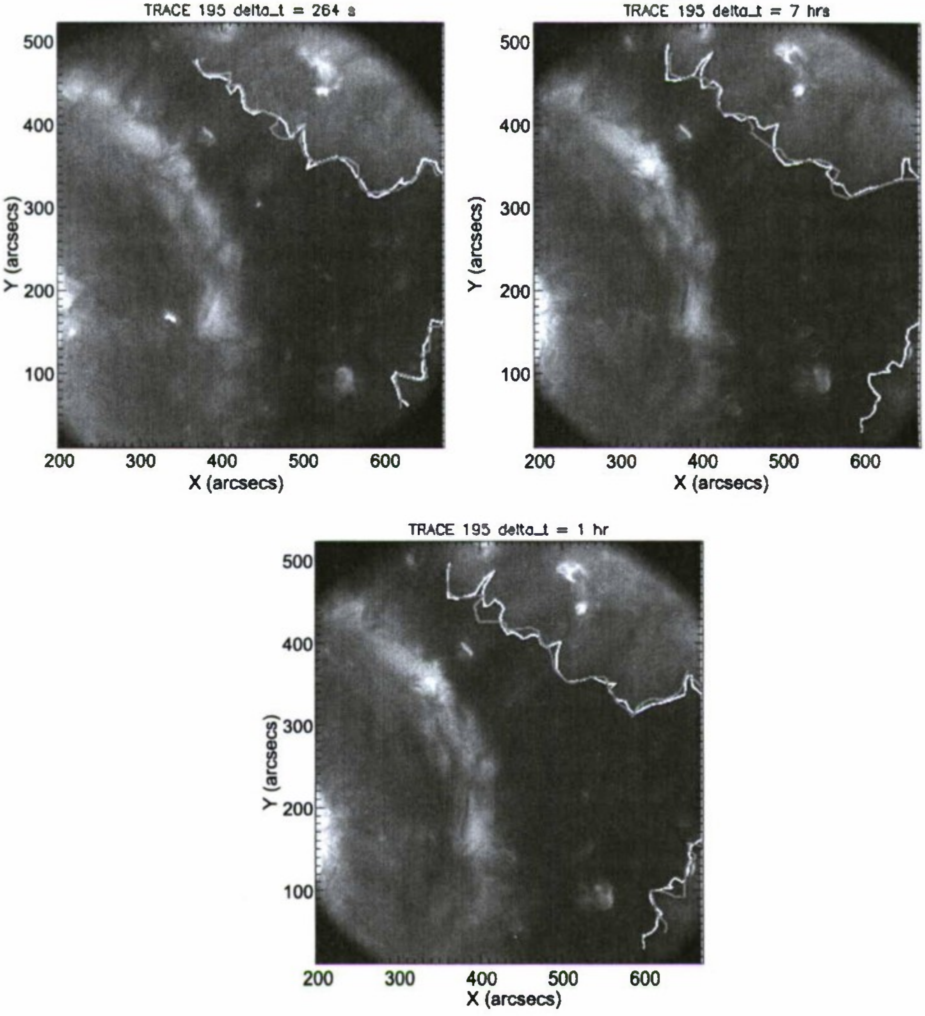


**Figure 6** CHB shifts observed over three different time scales on TRACE 195 Å images. In each case the earlier white and later gray CHBs are projected on the earlier image. Top left: CHBs at 13:20 UT and 13:25 UT showing the 4.4 minute differences. Top right: CHBs at 08:26 UT and 09:58 UT showing the 1.5 hour differences. Bottom: CHBs at 08:26 UT and 15:18 UT showing the 7 hour differences.

## 3.2. Active Regions at CHBs

Here we examined the dynamics only of a diffuse CHB, but earlier KH looked at interactions between CHs and adjacent active regions and found a more dynamic soft X-ray environment when the magnetic polarities of the active region loops opposed those of the CH, as would be expected for interchange reconnection. Recent observations have examined in more detail the roles played by active region loops at CHBs. Baker, van Driel-Gesztelyi, and Attrill (2007) observed with SOHO/EIT and MDI data likely magnetic reconnection between an active region and a preceding (westward) extension of the south polar CH in 2006 April. In their case the active region leading edge and CH polarities were opposite and therefore suitable for reconnection. More generally, Asai *et al.* (2008) showed that the predominate SXT active regions in CHs appear as anemone, characterized by a radial array of loops formed by connections between the CH fields and the opposite polarity part of the active region. The anemone active regions are generators of X-ray jets, consistent with the enhanced activity reported by KH for the active regions of their study with polarities opposite those of the CHs. A more sensitive indicator of reconnection events at CHBs might be radio emission. Active region sources of continuous micro-type III storms (Morioka *et al.*, 2007) lay predominately close to CHBs. These very low energy radio bursts could be indicators of continual small reconnection events at the CHBs, which are too weak to be observed at diffuse CHBs.

### 3.3. Implications for the SW Streams and CHB Layers

The enhanced magnetic interactions between active region fields and CHs are providing opportunities to study the source regions of the transitions between fast and slow solar wind flows. Harra *et al.* (2008) have observed a steady and pulsing material outflow from above an active region lying close to a trailing CH in February 2007. However, the CH and nearby active region shared matching positive polarity, and there was no obvious sign of CH interaction with the active region. Habbal, Scholl, and McIntosh (2008) found that the extension of unbalanced active region flux into neighboring active regions resulted in enhanced areal distributions of outflows and their gradients compared to outflows in the absence of active regions. Ko *et al.* (2006) associated solar wind abundance variations at 1 AU with a transition from a fast to a slow wind stream in October 1999 that they traced back with an MHD model to an active region that trailed a CH of the same magnetic polarity. The evidence for an association of some slow solar wind flows from active regions at CHBs now seems compelling, especially when the magnetic polarities are opposite and favorable for reconnection.

The Fisk (2005) model proposes that open field lines accumulate within CHs because the transport of open fields through the CHs via interchange reconnection can proceed only with the small loops that characterize the CH. The larger loops of the closed field regions allow bigger step displacements and faster open field line transport. In Section 1.1 and Figure 1 we noted that the magnetic polarity symmetry of the large closed fields at the E and W CHBs (KH) requires asymmetric reconnections by eastwardly propagating open field lines in the closed fields beyond the CHBs of quasi-rigid CHs. Those reconnections could proceed only at high altitudes with large loops or in small steps with small loops near the E CHB, but with the more favorable geometry at the W CHB they could proceed at lower altitudes and perhaps with a larger range of loop sizes. With our examination of only the western CHB of the 9 December 195 Å images we can not look for possible E – W differences in the CHB reconnections, but we note that KH made no such distinction in their CHB study. This suggests that the magnetic reconnections are similar in time and size scales on both CHBs, which presents a challenge to the concept of eastward transport of open field lines shown in the cartoons of Figure 1.

We now ask whether a possible E – W asymmetry in the CHB loop reconnections might be manifested in solar wind boundaries between fast and slow streams. Ulysses observations at solar minimum of solar wind properties at boundaries of fast and slow solar wind focused on the fast – slow SW transition regions, which originated near the trailing (E) CHBs and produced spatially extended rarefaction regions about 5× wider than the preceding slow – fast compression regions (Posner *et al.*, 2001). A Ulysses study of transition regions around nine fast solar wind streams at solar maximum (McComas, Elliott, and von Steiger, 2002) was restricted to high ($> 50°$) latitudes to avoid compression regions. These studies showed the presence of CHB layers (CHBLs) with gradually changing $O^{+7}/O^{+6}$ and Fe/O ratios rather than sharp transitions (McComas, 2003). No significant differences between were reported between the compressed slow – fast and rarefied fast – slow boundaries, so the CHBL modeling (Schwadron *et al.*, 2005a, 2005b) has focused on the fast–slow boundaries with an implicit assumption of symmetry at the two CHBLs, except for the obvious difference in time scales. A cursory comparison of the Mg/O, Fe/O, and $O^{+7}/O^{+6}$ ratios of the solar wind from the ACE/SWICS instrument during the October, November, and December passages of the high speed stream from the December 2000 CH shows higher ratios on the leading (W) boundary than on the trailing (E) boundary. This could indicate that higher and hotter (Feldman and Widing, 2003) loops are involved in reconnection on the W side than on the E side. This preliminary observational result must be tested further, but it suggests that an E–W asymmetry in the reconnection scenario, which is included in neither the Fisk (2005) model nor the current CHBL model of Schwadron *et al.* (2005a, 2005b), may be present in the two CHBLs surrounding low-latitude CHBs.

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